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Effect of Particle Impact Angle on Strength Degradation of Glass

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ANALYSES of the strength degradation suffered by glass surfaces in sharp-particle impact have recently been given in terms of elastic/plastic indentation fracture theory.^{1,2} These analyses emphasize the role of an essentially plastic contact in determining the driving forces for the ensuing microfracture; accordingly, hardness, as well as toughness, emerges as an important material parameter. Impact energy is found to be the controlling projectile parameter. With these parameters identified, it becomes possible to design ceramic systems for optimum resistance against strength loss in potentially dangerous contact situations.

However, all analyses to date have been carried out for the specific case of normally incident particles. It is important to estab-

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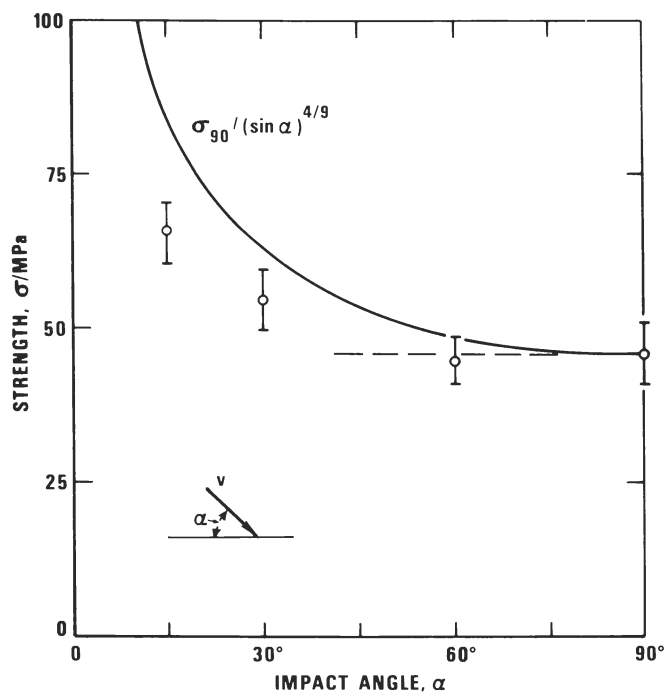


Fig. 1. Strength degradation of glass as function of impact angle for 100-mesh SiC particles at $v=94 \text{ m s}^{-1}$. Data points represent mean and standard deviation.

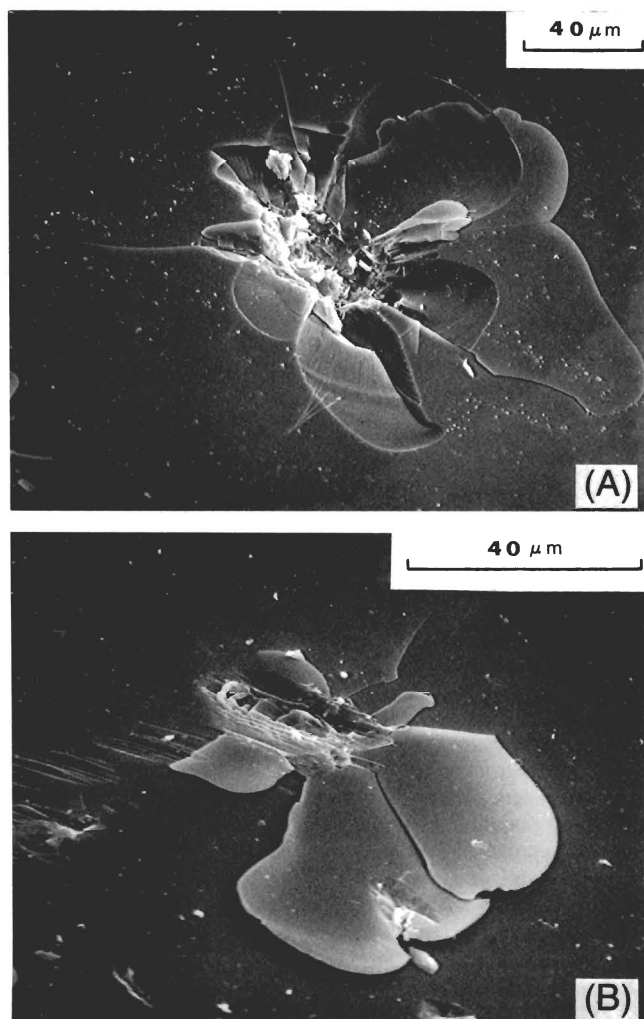


Fig. 2. Scanning electron micrographs of glass surfaces impacted with 100-mesh SiC particles at $v=94 \text{ m s}^{-1}$ for (A) $\alpha=90^\circ$ and (B) $\alpha=15^\circ$.

lish whether impact at oblique incidence can lead to any enhancement of the local damage level; if not, the existing analyses may be retained as a basis for conservative design. Such a study, by throwing light on the damage mechanisms themselves, might also be expected to add to the understanding of analogous angular effects in particle erosion phenomena.^{3,4}

Strength degradation tests were run on crown glass disks impacted with 100-mesh SiC-grit particles at a fixed velocity of 94 ms^{-1} , using the procedure described in Ref. 1. Runs were made at various specified impact angles, with a minimum of ten specimens per angle. Immediately after impactation, the target areas were covered with mineral oil to minimize kinetic effects in the subsequent strength tests. Rupture was effected in a ring-on-ring arrangement, the target face lying on the tension side; this test configuration conveniently avoided possible effects due to orientation between line of particle impact and direction of flexural tension. The results are shown as the data points in Fig. 1. Also shown in this figure is a solid curve representing the angular dependence of the strength, σ , as derived from the velocity-dependence relation $\sigma \propto v^{-4/9}$ (for given projectile and target) from Ref. 1; on the assumption that only the normal component of the velocity is effective in providing a driving force for the strength-degrading microcracks, this gives

$$\sigma_\alpha = \sigma_{90} / (\sin \alpha)^{4/9} \quad (1)$$

The observed strength degradation clearly diminishes as the impact occurs more obliquely; however, the observed strength degradation is clearly *more* than that predicted by the simple velocity resolution argument used to obtain Eq. 1.

Microscopic examination of actual damage sites gives some indication of angular effects additional to those embodied in Eq. (1). While substantial variation in the deformation/fracture pattern is observed from site to site on any given multiply-impacted surface, the comparative examples shown in Fig. 2 exhibit certain features which may be considered representative of their respective incident angles: first, the scale of the damage is indeed smaller at $\alpha=15^\circ$ than at $\alpha=90^\circ$, consistent with a reduced component of normal velocity; in addition, however, the pattern at oblique impact shows a marked tendency to elongation along the surface direction containing the plane of incidence, suggesting that the horizontal velocity component may well augment the crack driving forces. A complete analysis of this problem would appear to require a complex modification to the theory of elastic/plastic indentation fracture, with proper account taken of the effect of tangential loadings on both elastic and residual components of the contact stress field.⁵

¹ S. M. Wiederhorn and B. R. Lawn, "Strength Degradation of Glass Impacted with Sharp Particles: I," *J. Am. Ceram. Soc.*, **62** [1-2] 66-70 (1979).

² B. R. Lawn, D. B. Marshall, and S. M. Wiederhorn, "Strength Degradation of Glass Impacted with Sharp Particles: II," *ibid.*, pp. 71-74.

³ G. L. Sheldon and I. Finnie, "The Mechanism of Material Removal in the Erosive Cutting of Brittle Materials," *J. Eng. Ind.*, **88** [4] 393-400 (1966).

⁴ B. J. Hockey, S. M. Wiederhorn, and H. Johnson, pp. 379-402 in *Fracture Mechanics of Ceramics*, Vol. 3, Edited by R. C. Bradt, D. P. H. Hasselman, and F. F. Lange, Plenum, New York, 1978.

⁵ B. R. Lawn, A. G. Evans, and D. B. Marshall, "Elastic/Plastic Indentation Damage in Ceramics"; unpublished work.